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The importance of quantum decoherence in brain processes *

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Abstract

It is shown how environmental decoherence plays an essential and constructive role in a quantum mechanical theory of brain process that has significant explanatory power.

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1. Introduction

In a recent article with the same title as this one Max Tegmark[1] estimated how long it would take for interactions with the environment to destroy macroscopic quantum coherence in the brain. He arrived at the result 10^{-23} seconds. This tiny value appears, on the face of it, to rule out any significant role for macroscopic quantum effects in understanding the connection between brain processes and conscious thoughts. Indeed, Tegmark used his results to discredit Penrose's theory of consciousness.

Tegtmark noted that I also had developed a detailed theory of the mind-brain connection, but he did not direct his remarks about decohence at my theory. That would have made no sense, for his results are constructive rather than destructive in the context my theory, which is based heavily on the presumption that enviromental decoherence has a large effect on brain processes. My theory is specifically designed so that the particular quantum effects that allow a person's thoughts to influence his brain are not affected by environmental decoherence. This stringent requirement imposes non-trivial conditions on human behavior under controlled situations, and the empirical data gathered by psychologists during the past fifty years indicate that these detailed conditions are satisfied.

The foregoing remarks make it clear that the macroscopic quantum effects exploited in this quantum theory of the mind-brain system are *not* the macroscopic quantum effects used in quantum computation. Those latter effects are obliterated by environmental decoherence. Thus if brains really do operate in the way described by this theory then the technical ramifications could be far reaching: it would make available for development a type of macroscopic quantum effect that has been exploited by biological systems, but has not been been used in engineering. No new principle is involved here: the theory is simply a rational consequence of taking seriously the principles laid down by John von Neumann[2] and Eugene Wigner[3], together with reasonable and standard ideas about what brains do.

This theory has been described in a number of documents[4] designed

to inform neuroscientists and psychologists, but has not been described in a physics journal, in a form directed at physicists. The purpose of this paper to fill that void, and to show in particular how macroscopic quantum effects can be effective in a system that is decomposed into a mixture of nearly classical states on a time scale of 10^{-23} seconds. To establish that this theory is science, not mere speculative philosophy, I shall describe at the end some of the explanatory power of the theory.

My central task here is to explain how macroscopic quantum effects occurring in the presence of massive environmental decoherence can produce an action of mind on brain that can account for the detailed empirical facts. I assume that there is nothing special about a human brain except for its physical structure, and hence that other systems with similar functional structure should exhibit similar behaviour.

Many physicists are unfamiliar with the profound difference between the von Neumann/Wigner formulation of quantum theory and the more common Copenhagen formulation. So I will begin by describing the elements of the von Neumann/Wigner theory, before turning first to the central theoretical task, and then to confrontation with data.

2. The General Theory.

Bohr, Heisenberg, Dirac, Born, Pauli, and the other founders of quantum theory formulated their approach in a way that constituted a radical break with the classical physics that had preceeded it. They recognized, more explicitly than their immediate predecessors, that science was basically a human endeavour, and they defined the proper objective of science to be the construction of rules that would allow human beings to make useful prediction about connections between their observations. Thus human experiences were elevated to the status of the primary reality dealt with by the theory. Physicists were enjoined to desist from all efforts to understand the reality that lies behind their observations. Classical concepts were brought in through the fact that our description of how we set up our experiments, and what we learn from them, are—as a matter of fact—couched in the ordinary

language of everyday life, refined by the concepts of classical physics.

This way of understanding quantum theory is called the Copenhagen interpretation, and it is very useful: it allows physicists to get on with the job of testing the rules and applying them, without getting embroiled in the puzzling features that arise when one tries to dig deeper.

Von Neumann, however, did dig deeper. He noted that the measuring devices, which had a rather strange dual status in the Copenhagen approach, since they were physical objects, yet were descibed in classical language, were made up of the same kind of atomic constituents as the atomic systems that they were probing, and that there was therefore a well defined way to include these devices into the system that was described by the mathematical formulas of quantum theory, provided one brought into this description the entire physical universe, including our bodies and brains. This mathematical description was thereby elevated from its former status of being merely the language for the formulation of a mysterious set of rules for making predictions about our conscious experiences, to the status of a new kind of description of the physical universe. However, this description, unlike its classical predecessor, was dynamically linked to our conscious experiences. This dynamical linkage between the aspects of nature that were described in this mathematical language and the aspects of nature that we describe as the contents of our streams of conscious thoughts allowed physicists to obtain from a single unified theory all the predictions of Copenhagen quantum theory and all the valid prediction of classical physical theory from a dynamical theory that describes also the interaction between our minds and our brains. The key dynamical interaction is a change, in conjunction with each conscious experience, in the mathematically described universe: this change, called a 'reduction' or a 'collapse', tends to eliminate all those potentialities of the previously existing state that are incompatible with the expectations that characterize that experience.

This "reduction of the wave packet" is the basis of Copenhagen quantum theory. But von Neumann/Wigner quantum theory shifts the effect of

the reduction associated with a person's experience away from some external system, such as the measured atomic system, or the external measuring device, onto that person's brain. This placement is, from a scientific point of view, a far more reasonable positioning of the action of mind on matter, at least if one is trying to construct a theory of what is really happening. This placement creates the basis for a dynamical theory of how our conscious thoughts influence our brains. On the other hand, no commitment need be made as to the underlying connections between the realities that we describe as elements of our streams of conscious thoughts and the aspects of nature represented by the mathematical description of the physical world. For this theory is, in the final analysis, just a theory of the interplay between the aspects of nature that we describe in these two different ways, regardless of the true nature of the underlying realities.

To express these ideas in mathematical form let $S(t)$ represent the state of the universe at time t. Actually, the variable t labels a sequence Tomonaga-Schwinger[5] spacelike surfaces $\sigma(t)$ such that the whole surface moves gradually forward as t increases. I assume that for the study of brain dynamics quantum electro-dynamics will be adequate for the pertinent ranges of size and energies, and that future developments in elementary-particle physics will provide the necessary ultra-violet cut-off. I am imagining, for definiteness, that the surfaces $\sigma(t)$ will be the constant-time surfaces in the rest frame of the cosmic background radiation.

The state $S(t)$ is the *operator* form of the state: $S(t)/TrS(t)$ is the usual 'density matrix', where Tr stands for the trace operation.

The operator S can be represented by a matrix S_{ij}. If the system represented by S_{ij} is composed of n component parts, then the index i will consist of a sequence of n indices, and j will also be represented in this way. If b is the set of indices labelling some critical part of some person's brain, and $-b$ represents the complementary set of indices—i.e., the set of indices for rest of the universe—, then the state of this brain part, is represented by $S(t)_b = Tr_{-b}S(t)$, which is the partial trace of $S(t)$ over the complementary

set of variables $-b$. This operator $S(t)_b$ acts in the subspace of indices b associated with this brain part.

The basic problem to be faced is that the interaction of the brain with its environment will keep $S(t)_b$ in the form of a mixture of almost classical states, and that this would seem, on the face of it, to preclude macroscopic quantum effects of the kind needed for a quantum-mediated influence of mind on brain.

To see why that is not true one must understand what the brain is doing.

The job of the brain is basically to take clues, coming via sensors, about the situation of the body in its environment, and construct an appropriate plan of action, and then to initiate and supervise the execution of this plan. I assume that the evolutionary process has honed the properties of the mind-brain so that it performs this task well.

How do quantum effects enter into the behaviour of $S(t)_b$?

There is, of course, the basic fact that quantum theory is needed to make the chemistry work right. But in order to get directly to the essential point let me grant that the chemical interactions could be mocked up by some essentially classical-type model, and that the whole brain can be treated classically except for one thing: the migration of calcium ions within nerve terminals from the exits of micro-channels to the sites where they trigger the release into the synaptic cleft the contents of vesicles of neurotransmitter.

The diameters of the micro-channels in cerebral nerve terminals are approximately one nm [6], This means that the indeterminacy in the velocity of the migrating calcium ion that arises from the Heisenberg uncertainty principle is smaller than its thermal velocity by a factor of about 300. The distance between microchannel exit and trigger site is about 50nm [7]. Thus the uncertainty in the location of the calcium ion when it reaches the trigger site is of the order of size of the calcium ion itself. This means that the classical conception of the brain is inadequate in principle: quantum effects will generate a superposition of the classical state in which the neurotransmitter in the vesicle is released and the classical state in which this packet of neu-

rotransmitter is not released. This superposition will quickly be reduced to a mixture. A similar bifurcation occurs at each active nerve terminal. Hence the state $S(t)_b$ will necessarily evolve into a *mixture* of a huge number of states. Actually, a *continuum* of possible states will contribute, because each vesicle could be released a little earlier or a little later, and this will produce a continuum of contributing possibilities.

This first step is already important, because it shows that the idea that classical physics could give a deterministic answer to how the brain evolves is in principle wrong: that possibility is *strictly incompatible* with quantum theory, even if one ignores quantum effects associated with chemistry. Quantum effects entail that the brain state $S(t)_b$ will quickly evolve onto a mixture of quasi-classical possibilities, all of which are actually present, insofar as no actual collapse has occurred. It is important in what follows that the interaction with the environment, although it reduces superpositions to mixtures does it not reduce the mixture of quasi classical possibilities to a single one of these possibilies: all states of the mixture will continue to exist in parallel, insofar as the evolution is controlled by the Schroedinger equation.

It is, of course, well known that if one computes the expectation value of any operator in a state S that is a mixture of states S' then the result is identical to what would be obtained if the state were really in just *one* of the states S', but that one does not know which state S' this is, but does know the probability of each of the states S'.

This fact might suggest that there could be no way to distinguish a quantum model of the brain from a classical statistical model. However, that conclusion is incorrect, within the von Neumann/Wigner framework.

Within this vN/W framework each alert person has a stream of conscious experiences, and each such experience is associated with a reduction of the state of his brain to a form that is compatible with the experience: the reduction eliminates from the state of the brain all patterns of activity that are incompatible with that experience.

This reduction is represented mathematically in the following way. Each

experience E is associated with a projection operator $P(E)$, and the occurrence of E at time t has the following effect: if the symbol $t-$ signifies the action of taking the limit in which the argument of $S(t')$ tends to time t from times earlier than t, and $t+$ is related in the same way to later times, then

$$S(t+)_b = P(E)S(t-)_b P(E). \tag{1}$$

The projection operator P(E) acts in the subspace associated with the indices b, and satisfies the defining condition for projection operators $P(E)^2 = P(E)$. It acts on the brain state $S(t)_b$ to eliminate all patterns of activity or structure that are incompatible with E.

For example, if the experience E is an updating of the person's representation of the world, then P(E) will preserve in the mixture of quasi-classical states S' represented by $S(t)_b$ just those that contain the patterns of brain activity that will tend to etch into memory the experienced updating. If the experience is of an intention to cause one's body to move in a certain way then P(E) will eliminate from the mixture $S(t)_b$ those quasi-classical states S' that do not have the patterns of brain activity that will tend to cause the body to move in this way. These rules are just the analogs in the vN/W framework of the Copenhagen rule that the reduction is to the state that is compatible with the experience. But in the vN/W framework it may be supposed that this linkage of each experience E with a $P(E)$ that tends to produce the expected or intended future experiences is a consequence of the evolutionary development of the human system.

In any attempt to go beyond the Copenhagen interpretation of quantum theory the chief problem is the so-called "Basis Problem": What determines which *basis* will be used to reduce the myriads of possibilities produced by the quantum uncertainties to the individual reality that is experienced? Environmental decoherence is helpful, but it is not sufficient, because the quasi-classical states are over-complete, and hence do not provide a unique basis of normalizable states, and the structure of conscious experience is tied to the formation of quasi-stable and accessible memories, as Zurek emphasizes

in his excellent reviews [8].

Copenhagen quantum theory resolves the basis problem in a simple way: "The Observer", who stands outside the Hilbert space structure, decides how he will set up the experiments, and this decision fixes the "basis". This means that in the Copenhagen interpretation it is the 'free choice' on the part of the experimenter as to what he is interested in that fixes the basis.

The vN/W solution is essentially the same as the Copenhagen one: the basis is fixed by the experience of "the observer". Something beyond the Schroedinger evolution is needed to fix the basis, and this is taken to be "experience".

But then what fixes experience? How is E determined? And how does 'free choice' enter? The experience E cannot just pop out of nothing: it must be determined largely by the brain. Any adequate dynamical theory of the mind-brain must explain not only how mind effects brain, but also how brain affects mind.

The job of the mind and brain, acting together, is to determine the best course of action in the circumstances in which the mind-brain finds itself. The brain is busy grinding out, via the Schroedinger equation, the host of possibilities represented by the mixture $S(t)_b$. The 'best' option should be the one such that $P(E)$ has the greatest statistical weight. Let E(t) be the E that maximizes $TrS(t)_bP(E)$. This should be the best candidate for E at time t.

But the experiential events in the person's stream of consciousness occur only at discrete times, not continuously. Thus the 'free choice' can be reduced to *consent*, at certain instants t, to put to Nature the question of whether experience E(t) will occur. If E(t) does occur then $S(t+)$ becomes $P'(E(t))S(t-)P'(E(t))$, in accordance with (1). If Nature's answer is No, and hence E(t) does not occur at time t, then $S(t)$ becomes $(1-P'(E(t)))S(t-)(1-P'(E(t)))$, where the operator $P'(E(t))$ in these expressions is the trivial extension to the entire space of the operator $P(E(t))$ defined previously. The probability that the experience E(t) will occur is

given by

$$TrS(t)P'(E(t))/TrS(t) = Tr_b S(t)_b P(E(t))/Tr_b S(t)_b. \tag{2}$$

in accordance with the the basic probabilty rule of quantum theory.

The point of all this is that Copenhagen quantum theory introduced our conscious experiences directly into physical theory, and von Neumann/Wigner quantum theory tied these experiences to projection operators that act on the person's brain state in such a way as to bring the brain state into concordance with the experience. This converts quantum theory basically into a dynamical theory of the evolution of the universe that includes a theory of mind-brain interaction.

In this theory behaviour is largely controlled by the local mechanical brain process governed by the Schroeodinger equation. That process is 'local': the interactions are basically contact interactions. But there is one element that not governed by any known law of physics, namely the choices to consent or not consent at time t to putting to nature the question associated with the possible experience $E(t)$.

I do not intend to speculate at this point about how the evaluation that lies behind this choice is carried out. At the present early stage in the development of the science of the mind-brain system that question remains a project for future research. But the effect of a consent to 'put the question to nature', is to force Nature to return an answer, Yes or No, and the effect of the answer 'Yes', is to activate the process (2), which tends to produce to updating or action that characterizes the experience. This "reduction" of "collapse" process is macroscopic, in the sense that, according to the theory, the operator $P(E(t))$ acts instantaneously on some large part of the brain in accordance with process (1) descrbed above. I presume that the evaluation process has been honed by evolution so that it reflects the the likely consequences of activating process (1).

But in order for evolution to be able to hone this connection it is necessary that one's choice to consent has a likely effect on behaviour.

In order to compute the *likely* effects on behaviour one must add the properly weighted contributions from the two possible answers that nature might give. This is exactly what the famous von Neumann process 1 achieves: it gives the state that represents the effect of putting to nature the question $P = P(E(t))$ if no account is taken of which of the two possible answers, 'Yes' or 'No', nature returns.

The von Neumann process 1 is:

$$S(t)_b = PS(t-)_bP + (1 - P)S(t-)_b(1 - P). \tag{3}$$

So the key demand on the theory is that behaviour be controllable at the statistical level by applications at various times t of the process (3) associated with one's choice to give at time t the consent associated with the possible experience $E(t)$. And this control should tend to produce behaviour that conforms to the expectations and intentions imbedded in $E(t)$

Can one achieve this in a brain that is subject to massive effects of environmental decoherence? That is the question. The answer is Yes.

In order to consciously control one's behaviour one must normally keep attention focussed on a task for some period of time. Think of the focus of attention required to lift a heavy rock, or the focus of attention needed to fix into memory the details of some visual scene. In these clear examples of the apparent control of brain process by conscious effort some particular thought, or aspect of thought, remains fixed and stable the mind-brain for an experienced period of time. Hence we are led to consider the effect of putting the *same* question repeatedly to Nature in rapid succession.

Suppose, for definiteness, that the subsystem b is a set of degrees of freedom that is generating a contribution to the low frequency ($< 40Hz$) part of the coulomb part of the elecromagnetic field in the brain, and that the von Neuman process (3) repeats rapidly on this scale.

Let d represent the time interval between successive actions of process (3). Then

$$S(t + d)_b =$$

$$P(\exp -iHd)[PS(t-)_b P + (1-P)S(t-)_b(1-P)](\exp +iHd)P$$
$$+$$
$$(1-P)$$
$$(\exp -iHd)[PS(t-)_b P + (1-P)S(t-)_b(1-P)](\exp +iHd)$$
$$(1-P). \quad (4)$$

Because Hd is small in the subspace associated with b one can approximate the exponentials by $(1 \mp iHd)$, and observe that the terms linear in d drop out: the effect of a rapid repetition of process (3) is to damp out transitions between the two subspaces specified by P and $(1-P)$. This will be recognized as the familiar Quantum Zeno Effect [9].

What this means is that if a person can, by willful effort, acting through his power to consent, increase the rapidity of the events in his stream of consciousness then he could control the activity of his brain by keeping the activity of the b part of it confined to the subspace it is already in. The brain state would be prevented from "wandering" in the way that it would if there were no rapid quantum process (3). Thus willful effort would alter the behaviour of the quantum brain, at the statistical level, from what it would be if there were no macroscopic quantum effects.

Note that the Quantum Zeno Effect described above is not destroyed by the fact that $S(t)_b$ is a mixture: that makes no difference at all. The reason that the macroscopic quantum effect persists in the presence of decoherence is that it originates not in interference effects but rather the fact that it is the whole brain part associated with the set of variables b that enters into the dynamics, both at the level of specifying the 'best' possibility $P(E(t))$, and the associated action (3).

The key point is that the quantum theory of mind-brain described here gives each mind-brain the power, through force of will acting via consent, to keep its attention focussed on a task in a way that is impossible in the

analogous classical statistical model. And this effect is achieved by increasing, through effort of will, the rate of events in the stream of consciousness.

I stress again that this theory, although it is more congenial to ontological interpretation than the Copenhagen account, is basically just a way of organizing empirical features of the study of mind-brain systems in a way that is suggested by, and strictly compatible with, the basic laws and principles of physics.

3. Explanatory Power

Does this theory explain anything?

This theory was already in place [4] when a colleague brought to my attention some passages from “Psychology: The Briefer Course”, written by William James [25]. In the final section of the chapter on Attention James writes:

“I have spoken as if our attention were wholly determined by neural conditions. I believe that the array of *things* we can attend to is so determined. No object can *catch* our attention except by the neural machinery. But the *amount* of the attention which an object receives after it has caught our attention is another question. It often takes effort to keep mind upon it. We feel that we can make more or less of the effort as we choose. If this feeling be not deceptive, if our effort be a spiritual force, and an indeterminate one, then of course it contributes coequally with the cerebral conditions to the result. Though it introduce no new idea, it will deepen and prolong the stay in consciousness of innumerable ideas which else would fade more quickly away. The delay thus gained might not be more than a second in duration—but that second may be critical; for in the rising and falling considerations in the mind, where two associated systems of them are nearly in equilibrium it is often a matter of but a second more or less of attention at the outset, whether one system shall gain force to occupy the field and develop itself and exclude the other, or be excluded itself by the other. When developed it may make us act, and that act may seal our doom. When we come to the chapter on the Will we shall see that the whole drama of the voluntary life hinges

on the attention, slightly more or slightly less, which rival motor ideas may receive. ...”

In the chapter on Will, in the section entitled “Volitional effort is effort of attention” James writes:

“Thus we find that *we reach the heart of our inquiry into volition when we ask by what process is it that the thought of any given action comes to prevail stably in the mind.*”

and later

“*The essential achievement of the will, in short, when it is most ‘voluntary,’ is to attend to a difficult object and hold it fast before the mind. ... Effort of attention is thus the essential phenomenon of will.”*

Still later, James says:

“Consent to the idea’s undivided presence, this is effort’s sole achievement.” ...“Everywhere, then, the function of effort is the same: to keep affirming and adopting the thought which, if left to itself, would slip away.”

This description of the effect of mind on the course of mind-brain process is remarkably in line with what arose independently from a purely theoretical consideration of the quantum physics of this process. The basic features of the interplay between effort, attention, and control in the mind-brain system, as discerned by James, seem to come naturally out of the principles that von Neumann and Wigner promulgated in their effort to make physical sense of the mathematical rules that explain the connections between the phenomena from the realm of atomic physics. This opens up the interesting theoretical possibility of bringing the whole range of science from atomic physics to mind-brain dynamics together in a single rationally coherent theory of an evolving physical reality made essentially of objective knowledge or information rather than classically conceived matter.

A great deal has happened in psychology since the time of William James. A large amount empirical work pertaining to the issues at hand has been described in the book “The Psychology of Attention” by William Pashler [10]. This empirical work is basically behavioural: subjects are assigned multiple

tasks of various kinds and various loads, and their performances are measured. Pashler makes a powerful case for the conclusion that brain process is has two distinguishable subprocesses, one more analytical and perceptual and operating via parallel processing, the other more selective of action, and acting via a linear "bottleneck" process. The detailed features of these two processes appear to be well explained by the quantum model of the combined mind-brain system developed in this paper, with the parallel processing aspect being governed by the Schroedinger equation, and the selection bottleneck being govern by the collapse process.

I am not claiming that no classical model could explain these features. But the fact that the details seem to be forced in the quantum approach by the severe constraints imposed by the existence of strong environmental decoherence makes the quantum model more theoretically attractive than a classical model that puts these features, ad hoc, into a theoretical structure in which consciousness can make no difference.

This journal is not the appropriate place to describe the detailed ways in which the empirical findings described by Pashler support the theory described above. A discussion of this matter can be found elsewhere [11].

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